

Ion Pairs in the Solvolysis of Secondary Systems. Salt Effect, ^{18}O -Labeling, and Polarimetric Studies of 1-(4'-Tolyl)-2,2,2-trifluoroethyl Tosylate

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Abstract: The effect of added trifluoroacetate and triflate salts on the trifluoroacetylation of 1-(4'-tolyl)-2,2,2-trifluoroethyl tosylate has been studied, including reactions of optically active and ^{18}O -labeled substrates. With no added salt the polarimetric rate constant k_{α} exceeds the solvolytic rate constant k_{UV} by a factor of 14.7, corresponding to a fraction 0.93 of ion pair return with racemization. On the addition of trifluoroacetate or triflate salts there is a large initial curved acceleration of k_{UV} , characteristic of the special salt effect, with a smaller linear increase in k_{α} . The ^{18}O scrambling observed in the unsolvolyzed starting material during trifluoroacetylation corresponds to fractions of return with scrambling of 0.94 and 0.46 at $[\text{NaO}_2\text{CCF}_3] = 0.0$ and 0.201 M, respectively, as compared to fractions of return of 0.93 ± 0.01 and 0.37 ± 0.01 determined from k_{α} , showing that scrambling is the same or modestly more efficient than racemization in the ion pairs. The decrease in the k_{α}/k_{UV} ratio appears to level off to values between 1.07 and 1.48 for [salt] between 0.588 and 0.601 M, consistent with the presence of intimate ion pairs that are not captured by salt. The effect of the salts on k_{UV} is quantitatively correlated by kinetic expressions derived for the reversible formation of ion pairs which undergo competitive return to starting material and reaction with solvent or salt leading to product. The addition of 0.1 and 0.3 M NaOTs causes common ion rate depression of k_{UV} by factors of 13 and 10%, respectively, consistent with the formation and capture of dissociated ions as reactive intermediates in these reactions. The presence of 0.260 M NaOTs causes an increase in k_{α} of 17%, consistent with a normal salt effect on racemization of an ion pair.

The study of the effects of salts on reactivity has long been a topic of major interest in organic chemistry. An extensive series of studies of solvolytic reactivity by Winstein *et al.*¹ utilized the effects of salts to investigate the role of ion pairs in these processes and revealed the occurrence of special salt effects, which are strong accelerations of the reactions due to the capture of solvent-separated ion pairs at low salt concentrations. The study of salt effects and ion pairs has continued to find wide application^{2a,b} and has utilized new techniques including the effects of salts on ion pairs generated by laser flash photolysis.^{2c,d}

The effects of salts on other reactions is also attracting increasing interest, including the catalysis of the Diels–Alder reaction by various metal perchlorates, which parallels the ability of these salts to coordinate with the carbonyl oxygen of acetone.³

The study of salt effects on ion pairs continues,^{4a,b} and other recent related investigations involve the behavior of ion–molecule pairs,^{4c,d} solvated carbocations,^{4e} and ion pairs from alkene protonations.^{4f}

We have recently reported the occurrence of very large salt effects on the trifluoroacetylation of predominantly tertiary benzylic substrates substituted with carbocation-destabilizing CF_3 groups.^{5a} It was found that NaO_2CCF_3 and KO_2CCF_3 showed the behavior characteristic of the Winstein special salt effect on the substrates, namely a sharp curved initial increase in the rate, followed by more modest increases in the rates at higher [salt]. For the first time kinetic expressions were derived and successfully applied to correlate the dependence of rate on [salt] over the entire range of [salt].^{5a}

In particular, for the general Winstein mechanism shown in eq 1, the simplified scheme of eqs 2 and 3 was used to derive the kinetic expression of eq 4, where the constants k_{o} and K_{app} were defined as in eqs 5 and 6. This scheme was used to account for the effects of salts on substrates such as 1^{5b} and

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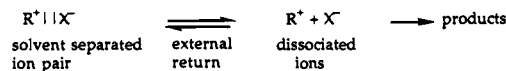
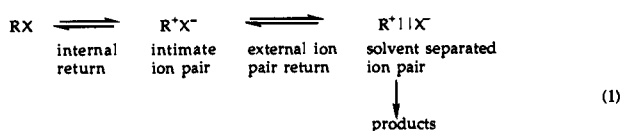
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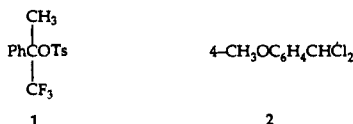
2.^{5c} An expanded version of eq 4 was originally derived by Winstein *et al.*^{1e} and was applied by a graphical method at low [salt].



$$k_{\text{obs}} = (k_2 K_{\text{app}} + k_1[\text{salt}]) / (K_{\text{app}} + [\text{salt}]) \quad (4)$$

$$k_2 = k_1 k_2 / (k_{-1} + k_2) \quad (5)$$

$$K_{\text{app}} = (k_{-1} + k_2) / k_1 \quad (6)$$



In addition to salt effects the use of optically active and ¹⁸O-labeled substrates provides very powerful tools for the study of solvolytic behavior,^{4d,6,7} and we now report the application of both of these techniques to elucidate the behavior of the ion pairs formed in the solvolysis of 1-(4'-tolyl)-2,2,2-trifluoroethyl tosylate (**3**). The study of the effects of salts is extended to include not only trifluoroacetates but also triflates to determine the generality of their remarkable behavior. The substrate **3** was chosen because of its convenient reactivity and its suitability for both stereochemical and ¹⁸O-labeling studies.

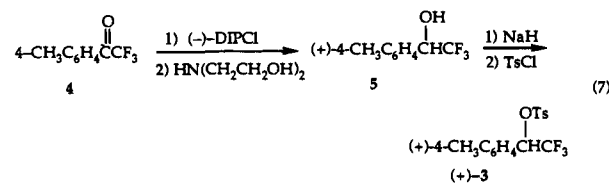
For studies of ¹⁸O scrambling we have utilized the improved method introduced by us^{6a} of measuring the ¹³C NMR peak areas of recovered starting material. The ¹⁸O-isotope effect produces a differential chemical shift on the O-substituted carbon, permitting quantitative measurement of the extent of ¹⁸O scrambling.^{6a} This method is more convenient than mass spectrometric methods utilized previously.^{7d}

The validity of this method was established^{6a,e} by comparison to mass spectrometric results of Denny and Goldstein for 2-phenyl-1-propyl sulfonates,^{7e} in which both methods found no scrambling in recovered primary sulfonate and 43 ± 4% scrambling in rearranged sulfonate after about one half-life for acetolysis. Similarly we find a minimum fraction of ion pair return by our method of 0.72 in the acetolysis at 75 °C of 2-adamantyl tosylate,^{6c} as compared to a value of 0.73 found

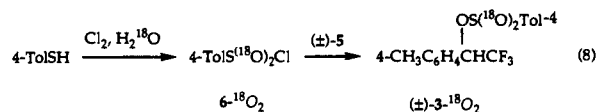
by Paradisi and Bunnett^{7d} for 2-adamantyl benzenesulfonate in acetic acid containing 0.04 M NaOAc at 80 °C.

Results

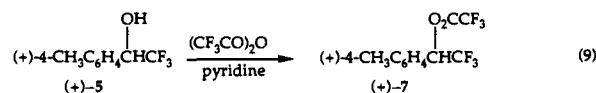
Optically inactive tosylate **3** was prepared as reported previously.^{5b} For the preparation of optically active substrate, reduction of 4-tolyl trifluoromethyl ketone (**4**) with (-)-*B*-diisopinocampheylchloroborane [(-)-DIPCl, Aldrich]⁸ followed by chromatography gave (+)-**5**, mp 43–43.5 °C. Comparison of the observed rotation to that reported by Ohno *et al.*⁹ suggested that the purified alcohol was obtained in 100% ee, consistent with results obtained for the reduction of other aryl alkyl ketones with this reagent,^{8c} which gives reduction of phenyl trifluoromethyl ketone with 90% ee.^{8b} Alcohol **5** was converted to the tosylate **3** by reaction with NaH and TsCl (eq 7).



Reaction of 4-toluenethiol with Cl₂ and H₂¹⁸O gave 4-tosyl chloride-¹⁸O (**6-¹⁸O**), as described by Oae *et al.*¹⁰ and this reacted with (±)-**5** to give (±)-**3-¹⁸O** (eq 8).



Rate constants for trifluoroacetolysis of (±)-**3**, measured using UV spectroscopy as previously,^{5b} are reported as *k*_{UV} values (Table 1). This reaction has been previously shown to lead to the trifluoroacetate **7** as the only observed product.^{5b} Values of *k*_{UV} were determined at different concentrations of added LiClO₄, the trifluoroacetate salts NaO₂CCF₃, LiO₂CCF₃, and KO₂CCF₃, and the trifluoromethanesulfonate salts LiO₃SCF₃ and NaO₃SCF₃, as well as the common ion salt NaOTs, and these are collected in Table 1. Polarimetric rate constants *k*_α were measured for (+)-**3** as a function of salt concentration, and these are also given in Table 1. Plots comparing the effect of each of the salts on *k*_α and *k*_{UV} are shown in Figure 1 a–f. The authentic product (+)-**7** was prepared by the reaction of (+)-**5** with trifluoroacetic anhydride (eq 9). In the *k*_α measurements, the observed rotations decreased to zero, and from the rotation of (+)-**7**, 10% of residual optical activity could have been detected.



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Table 1. Salt Effects on Polarimetric (k_a) and Spectroscopic Rates (k_{UV}) for Trifluoroacetylation of 1-(4-Methylphenyl)-2,2,2-trifluoroethyl Tosylate at 25 °C

salt	[salt], M	k_{UV} , s ⁻¹	k_a , s ⁻¹	k_a/k_{UV}	1 - F ^a	
LiClO ₄	0.0991	1.02 × 10 ⁻³	1.40 × 10 ⁻³	1.37	0.27	
	0.0793	9.04 × 10 ⁻⁴	1.38 × 10 ⁻³	1.52	0.34	
	0.0595	7.10 × 10 ⁻⁴	1.31 × 10 ⁻³	1.84	0.46	
	0.0397	5.01 × 10 ⁻⁴	1.11 × 10 ⁻³	2.22	0.55	
	0.0198	3.68 × 10 ⁻⁴	9.46 × 10 ⁻⁴	2.56	0.61	
	0.588	1.73 × 10 ⁻³	1.92 × 10 ⁻³	1.10	0.10	
	0.441	1.47 × 10 ⁻³				
	0.404		1.74 × 10 ⁻³			
	0.294	1.08 × 10 ⁻³	1.47 × 10 ⁻³	1.36	0.27	
	0.206	7.84 × 10 ⁻⁴				
LiO ₂ CCF ₃	0.202		1.22 × 10 ⁻³			
	0.1175	5.25 × 10 ⁻⁴	1.08 × 10 ⁻³	2.06	0.51	
	0.0588	3.11 × 10 ⁻⁴	9.91 × 10 ⁻⁴	3.19	0.69	
	0.0294	1.94 × 10 ⁻⁴	9.32 × 10 ⁻⁴	4.80	0.79	
	0.601	1.20 × 10 ⁻³	1.77 × 10 ⁻³	1.48	0.32	
	0.588		1.86 × 10 ⁻³			
	0.501	1.18 × 10 ⁻³	1.59 × 10 ⁻³	1.35	0.26	
	0.481		1.57 × 10 ⁻³			
	0.420	1.09 × 10 ⁻³		(1.6) ^b	(0.38) ^b	
	0.411		1.77 × 10 ⁻³			
NaO ₂ CCF ₃	0.300	8.82 × 10 ⁻⁴		(1.6) ^b		
	0.294		1.44 × 10 ⁻³			
	0.209		1.19 × 10 ⁻³	(1.6) ^b		
	0.201	7.34 × 10 ⁻⁴	(1.17 × 10 ⁻³) ^b	(1.6) ^b		
	0.120	4.94 × 10 ⁻⁴		(2.0) ^b	(0.50) ^b	
	0.118		9.96 × 10 ⁻⁴			
	0.0600	3.20 × 10 ⁻⁴		(2.9) ^b	(0.66) ^b	
	0.0588		9.38 × 10 ⁻⁴			
	0.0	5.47 × 10 ⁻⁵	8.02 × 10 ⁻⁴	14.7	0.93	
	KO ₂ CCF ₃	0.586	1.48 × 10 ⁻³	1.58 × 10 ⁻³	1.07	0.06
0.535		1.40 × 10 ⁻³	1.57 × 10 ⁻³	1.12	0.11	
0.451		1.29 × 10 ⁻³	1.46 × 10 ⁻³	1.13	0.12	
0.375		1.26 × 10 ⁻³	1.51 × 10 ⁻³	1.20	0.17	
0.293		1.14 × 10 ⁻³	1.37 × 10 ⁻³	1.20	0.17	
0.214		9.86 × 10 ⁻⁴	1.32 × 10 ⁻³	1.33	0.25	
0.169		8.74 × 10 ⁻⁴	1.16 × 10 ⁻³	1.33	0.25	
0.117		6.71 × 10 ⁻⁴	1.09 × 10 ⁻³	1.62	0.38	
0.0586		4.80 × 10 ⁻⁴	9.70 × 10 ⁻⁴	2.02	0.51	
0.0293		2.88 × 10 ⁻⁴	9.02 × 10 ⁻⁴	3.13	0.68	
LiO ₃ SCF ₃	0.590	1.88 × 10 ⁻³				
	0.436	1.39 × 10 ⁻³	1.97 × 10 ⁻³	1.42	0.29	
	0.295	1.06 × 10 ⁻³	1.73 × 10 ⁻³	1.63	0.39	
	0.218	9.34 × 10 ⁻⁴	1.38 × 10 ⁻³	1.48	0.32	
	0.1181	5.39 × 10 ⁻⁴	1.08 × 10 ⁻³	2.00	0.50	
	0.0590	3.21 × 10 ⁻⁴	(9.42 × 10 ⁻⁴) ^b	(2.93) ^b	(0.66) ^b	
	0.0295	2.00 × 10 ⁻⁴	9.38 × 10 ⁻⁴	4.69	0.79	
	NaO ₃ SCF ₃	0.601	1.31 × 10 ⁻³	1.70 × 10 ⁻³	1.30	0.23
		0.450	1.21 × 10 ⁻³			
		0.300	9.46 × 10 ⁻⁴	1.34 × 10 ⁻³	1.42	0.29
0.210		7.54 × 10 ⁻⁴				
0.120		5.24 × 10 ⁻⁴	1.10 × 10 ⁻³	2.10	0.52	
0.0601		3.32 × 10 ⁻⁴	(9.80 × 10 ⁻⁴) ^b	(3.4) ^b	(0.66) ^b	
NaOTs	0.0300	2.23 × 10 ⁻⁴	9.66 × 10 ⁻⁴	4.33	0.77	
	0.300	4.19 × 10 ⁻⁵				
	0.260		8.45 × 10 ⁻⁴			
	0.0967	4.08 × 10 ⁻⁵				
0.0 ^c	4.71 × 10 ⁻⁵	7.23 × 10 ⁻⁴	15.4	0.935		

^a 1 - F = 1 - (k_{UV}/k_a), estimated error ±0.01. ^b Interpolated value.

^c Rate remeasured using the same batch of solvent as for those with added NaOTs.

For the measurement of ¹⁸O scrambling in (±)-**3**-¹⁸O₂, reaction samples in the appropriate solvents were quenched and extracted at intervals and the ¹³C spectra were taken. The signal of the alkoxy carbon of the starting tosylate appeared as a quartet due to C-C-F coupling (²J_{CF} = 33.9 Hz), and the peak due to the ¹⁸O-induced isotope shift was observed at 0.029 ppm (2.0 Hz) higher field, as illustrated in Figure 2. The ratio of ¹⁶O-bonded and ¹⁸O-bonded carbons (R¹⁶OTs and R¹⁸OTs, respectively) were determined by integration, as summarized in Table 2.

In Table 2 are given the concentration of unreacted tosylate derived from the corresponding solvolysis rate constants k_{UV} using calculated ratios of [product], [R¹⁶OTs], and [R¹⁸OTs] obtained from eq 10 and the derived expression eq 11. On the assumption that the oxygen scrambling involves complete exchange of the three oxygen atoms the concentration of unscrambled tosylate is calculated by eq 12.

$$[\text{total ROTs}] = [\text{R}^{16}\text{OTs}] + [\text{R}^{18}\text{OTs}] = e^{-k_{UV}t} \quad (10)$$

$$\ln[\text{R}^{18}\text{OTs}] = -\ln([\text{R}^{16}\text{OTs}]/[\text{R}^{18}\text{OTs}] + 1) - k_{UV}t \quad (11)$$

$$[\text{unscrambled ROTs}] = [\text{R}^{16}\text{OTs}] - [\text{R}^{18}\text{OTs}]/2 \quad (12)$$

The minimum rate of ionization k_i is obtained from the decrease in [unscrambled ROTs] by eq 13. The rate constants k_{UV} and k_i are listed in Table 2, together with the minimum fraction of ion pair return, 1 - F, obtained by eq 14. Because

$$k_i = -(1/t)\ln([\text{R}^{16}\text{OTs}] - [\text{R}^{18}\text{OTs}]/2)/100 \quad (13)$$

$$1 - F = 1 - (k_{UV}/k_i) \quad (14)$$

of the partial overlap of the ¹³C signals (Figure 2), the ¹⁶O/¹⁸O ratios were measured at two different reaction times, and good agreement was obtained for the 1 - F values, confirming the reliability of the method.

Discussion

The additions of LiClO₄ and the trifluoroacetate and triflate salts all cause very large increases in the solvolytic rate constants k_{UV} for **3** (Figure 1), as observed previously for the former salts with other destabilized benzylic substrates.^{5a} The rate acceleration for LiClO₄ is significantly larger than for the trifluoroacetate and triflate salts, and contrary to the results found previously, modest curvature in the plot is observed within the range of solubility of this salt. The data for the six salts are described by eq 4, with the fitted constants k_1 and K_{app} given in Table 3. This equation is derived from the processes of eqs 2 and 3, where an ion pair intermediate undergoes competitive return to the starting material, reaction with solvent, and reaction with salt. The good fits of eq 4 to the k_{UV} data are supportive of this mechanism.

The effect of the different trifluoroacetate salts on the reaction of **3** are similar but not identical, as shown in Figure 1 and by the derived parameters in Table 3. Previously^{5a} reported data on **1** also showed modest differences between salts, with the rate ratio $k(\text{KO}_2\text{CCF}_3)/k(\text{NaO}_2\text{CCF}_3)$ ranging from 1.15 at 0.03 M salt to 0.80 at 0.6 M salt. For **3** this ratio is 1.5 at 0.06 M salt and 1.23 at 0.6 M salt. The effects of the triflate salts LiO₃-SCF₃ and NaO₃SCF₃ are qualitatively very similar to those of the trifluoroacetate salts, with triflate/trifluoroacetate ratios of 1.09 at 0.6 M salt for both the lithium and sodium cations. At 0.6 M salt the relative reactivities for the Li, Na, and K cations are 1.44, 1.00, and 1.23 for the trifluoroacetate salts and for Li and Na are 1.44 and 1.00 for the triflates. The origin of the small differences is not certain but is clearly not dependent only on cation size.

Thus it appears that the major effects of the trifluoroacetate and triflate salts are largely independent of the specific cation and anion, although there are differences in the rate accelerations of the rate constants by the different salts, and crossovers in the plots are observed for **3** (KO₂CCF₃ and LiO₂CCF₃) and **1** (KO₂CCF₃ and NaO₂CCF₃).^{5a} Added LiClO₄ causes a greater acceleration of k_{UV} than do LiO₂CCF₃ and LiO₃SCF₃, by a factor of about 2 at 0.1 M salt. The origin of this effect is indicated by the derived kinetic parameters in Table 3, in which the value

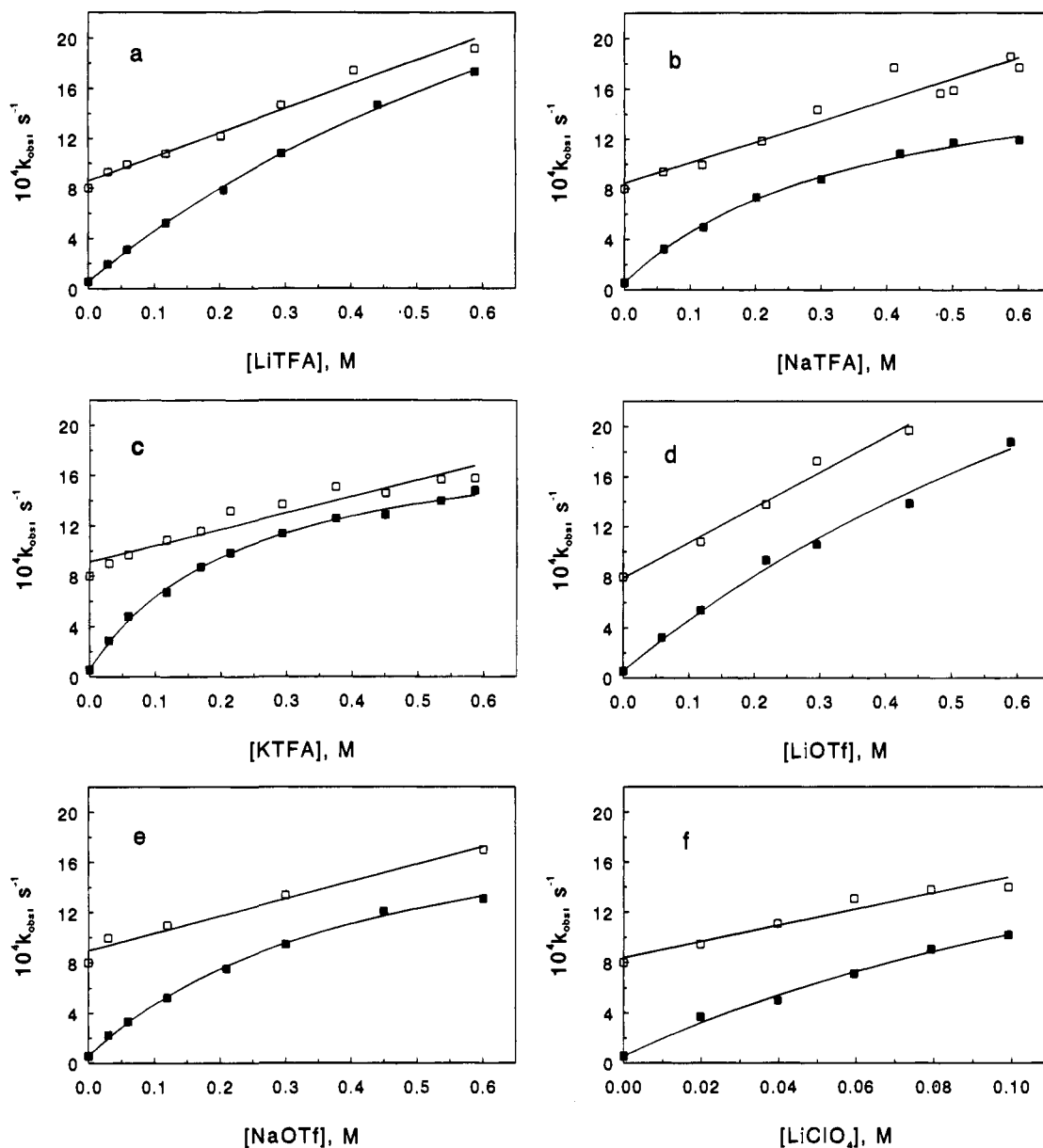


Figure 1. Rate constants k_{α} (open symbols) and k_{UV} (solid symbols) versus [salt] for (a) LiO_2CCF_3 , (b) NaO_2CCF_3 , (c) KO_2CCF_3 , (d) LiO_3SCF_3 , (e) NaO_3SCF_3 , and (f) LiClO_4 .

of k_i/k_s (the ratio of the rate constants for capture of the solvent separated ion pair by salt and by solvent) is larger for LiClO_4 compared to the trifluoroacetates and triflates by factors of 1.7–3.4. This is consistent with the greater acceleration in k_{UV} induced by LiClO_4 and provides a quantitative measure of the greater efficiency of LiClO_4 in capturing ion pairs.

Polarimetric Rates. With no added salt k_{α} exceeds the solvolysis rate constant k_{UV} for **3** by a factor of 14.7. This observation confirms the high degree of ion pair return for this substrate, but it is only a minimum estimate, as ionization of the substrate followed by return without racemization presumably occurs to a significant extent.

With increasing [salt] there is a small and approximately linear increase in k_{α} that is essentially the same for the trifluoroacetates and triflates, which gives accelerations from the initial value of $0.802 \times 10^{-3} \text{ s}^{-1}$ to values of $(0.946\text{--}1.44) \times 10^{-3} \text{ s}^{-1}$ for the different salts at 0.3 M (Table 1). Above this salt concentration the increase in k_{α} partially or totally levels off, with rate constants in 0.586–0.601 M salt of $(1.31\text{--}1.92) \times 10^{-3} \text{ s}^{-1}$ for the different trifluoroacetates and triflates, with the largest rate constants for the two Li salts. The accelerations

in the solvolysis rate constants k_{UV} at the lower salt concentrations are significantly more than those in the polarimetric rate constants, and so the rate ratios k_{α}/k_{UV} rapidly decrease from the value of 14.7 with no added salt to values at 0.586–0.601 M salt of 1.07–1.48, with the same behavior for the trifluoroacetates and triflates.

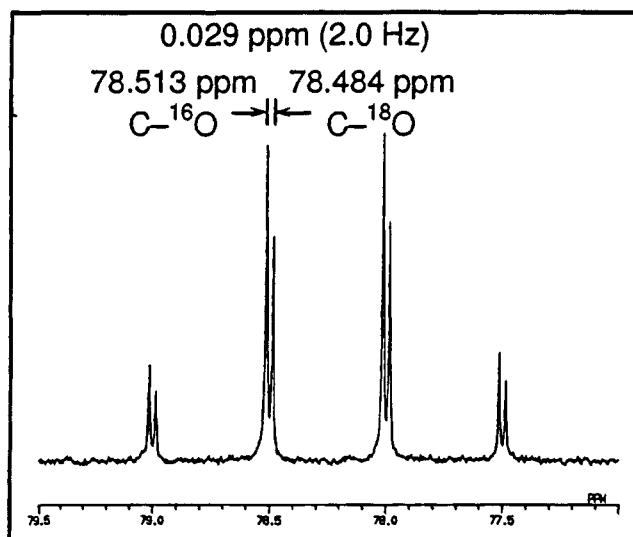
The much larger value of k_{α} compared to k_{UV} at lower [salt] confirms that in the absence of salt return of ion pairs to starting materials occurs to a major extent and is consistent with the mechanism of eq 1, in which salt is capturing only solvent-separated ion pairs. The absence of a large effect of added salt on k_{α} indicates that racemization occurs before capture of the solvent-separated ion pairs by salt.

The value of k_{α} provides a minimum estimate of the value of k_i , the rate constant for ionization, and analogously to eq 15 the minimum fraction of ion pair return $1 - F$ equals $1 - (k_{UV}/k_{\alpha})$, as collected in Table 1. At [salt] = 0 and $k_{\alpha}/k_{UV} = 14.7$, $1 - F = 0.93$, while at 0.201 M NaO_2CCF_3 this equals 0.37. For the other trifluoroacetates and triflates $1 - F$ has similar values of 0.25–0.38 near 0.23 M salt. This drops to a lowest value of 0.063 at $[\text{KO}_2\text{CCF}_3] = 0.586 \text{ M}$, which is a minimum

Table 2. NMR Analysis of Solvolysis of 1-(4'-Tolyl)-2,2,2-trifluoroethyl Tosylate-sulfonyl- $^{18}\text{O}_2$

solvent	time (min)	$^{16}\text{O}/^{18}\text{O}^a$	component (%)				$k_{\text{UV}} (\text{s}^{-1} \times 10^5)$	$k_i^d (\text{s}^{-1} \times 10^5)$	$1 - F^e$
			[product] ^b	[^{16}OTs]	[^{18}OTs]	[ROT c]			
all	0		0.00	100.00	0.00	100.00			
EtOH ^f	900	2.664	78.77	15.44	5.79	12.55	2.87 ^j	3.843	0.253
		2.668	78.77	15.44	5.79	12.55		(3.843)	(0.25 ± 0.00)
80A ^f	300	2.659	68.63	22.80	8.57	18.51	6.44 ^k	9.371	0.313
		2.539	68.63	22.50	8.87	18.07		9.504	0.322
	500	1.689	85.51	9.10	5.39	6.41		9.159	0.297
		1.650	85.51	9.02	5.47	6.29		9.222	0.302
						(9.31 ± 0.13)	(0.31 ± 0.01)		
AcOH ^f	100	1.931	30.02	46.10	23.88	34.16	5.95 ^j	17.90	0.667
		1.934	30.02	46.13	23.85	34.21		17.88	0.667
	150	1.333	41.46	33.44	25.10	20.90		17.40	0.658
		1.368	41.46	33.82	24.72	21.46		17.10	0.652
						(17.6 ± 0.3)	(0.66 ± 0.01)		
97TFE ^g	400	3.650	21.34	61.74	16.92	53.28	1.00 ^j	2.623	0.618
		3.808	21.34	62.30	16.36	54.12		2.558	0.609
	800	1.950	38.12	40.90	20.98	30.41		2.480	0.596
		1.983	38.12	41.14	20.74	30.77		2.456	0.592
						(2.53 ± 0.07)	(0.60 ± 0.02)		
97HFIP ^h	100	3.292	28.79	54.62	16.59	46.33	5.66 ^j	12.82	0.559
		3.191	28.79	54.22	16.79	45.73		13.04	0.566
	200	1.533	49.30	30.68	20.02	20.68		13.14	0.569
		1.498	49.30	30.40	20.30	20.26		13.31	0.575
						(13.1 ± 0.2)	(0.57 ± 0.01)		
TFA ^h	10	2.587	3.23	69.79	26.90	56.34	5.47 ^j	95.63	0.943
		2.619	3.23	70.03	26.74	56.66		94.68	0.942
	20	1.257	6.35	52.15	41.50	31.40		96.53	0.943
		1.316	6.35	53.21	40.44	32.99		92.41	0.941
						(94.8 ± 1.5)	(0.94 ± 0.00)		
TFA ^{h,i}	10	3.690	35.62	50.65	13.73	43.79	73.4 ^j	137.6	0.467
		3.658	35.62	50.56	13.82	43.65		138.2	0.469
	12	3.324	41.05	45.32	13.64	38.50		132.5	0.446
		3.131	41.05	44.68	14.27	37.55		136.0	0.460
						(136 ± 2)	(0.46 ± 0.01)		

^a $^{16}\text{O}/^{18}\text{O}$ ratio for peak at 78.5 ppm (upper entry) and 78.0 ppm (lower entry). ^b Calculated from K_{UV} by using eq 10. ^c Unscrambled ROTs, calculated by eq 12. ^d Minimum rate of ionization from eq 13. ^e Minimum fraction of internal return from eq 14. ^f 115 °C. ^g 45 °C. ^h 25 °C. ⁱ In the presence of 0.201 M NaO_2CCF_3 . ^j Reference 5b. ^k Liu, K. T.; Yang, J. S.; Chang, S. M.; Lin, Y.-S.; Sheu, H.-C.; Tsao, M. L. *J. Org. Chem.* **1992**, 57, 3041–3046. ^l Present work.

**Figure 2.** ^{13}C NMR signal for carbonyl carbon of partially scrambled 1-(4'-tolyl)-2,2,2-trifluoroethyl tosylate-sulfonyl- $^{18}\text{O}_2$ ($3\text{-}^{18}\text{O}_2$).

estimate of the extent of ion pair return that occurs, as return without racemization is expected to be significant, due to the considerable reorganization of the initial ion pair required for racemization to occur.

Thus the rate ratio k_{α}/k_{UV} rapidly decreases from 14.7 in the absence of salt to values of 1.07–1.48 at salt concentrations of 0.588–0.601 M, and while at these concentrations the ratio has

Table 3. Fitted Constants and Derived Kinetic Parameters for Salt Effects on Trifluoroacetolysis of **3**, Based on Eq 4^a

salt	$10^3 k_1, \text{s}^{-1}$	K_{app}, M	k_{-1}/k_s	$k_i/k_s, \text{M}^{-1}$
LiO_2CCF_3	4.95 ± 0.37	1.12 ± 0.12	89 ± 7	81 ± 15
NaO_2CCF_3	1.99 ± 0.10	0.384 ± 0.04	35 ± 2	95 ± 15
KO_2CCF_3	1.99 ± 0.05	0.232 ± 0.016	35 ± 1	157 ± 15
LiO_3SCF_3	5.82 ± 1.32	1.33 ± 0.40	105 ± 24	80 ± 42
NaO_3SCF_3	2.24 ± 0.10	0.428 ± 0.038	40 ± 2	96 ± 13
LiClO_4	2.97 ± 0.75	0.200 ± 0.070	53 ± 14	270 ± 160

^a Obtained from the variation of k_{UV} with [salt] (Table 1), by a two-parameter fit (k_1 and K_{app}) of eq 4, keeping k_0 fixed at the observed value of $5.47 \times 10^{-5} \text{ s}^{-1}$. The cited uncertainties in k_1 and K_{app} are the standard errors from the nonlinear fitting. Correlation coefficients were in the range 0.9965–0.9995. The derived parameters are $k_{-1}/k_s = (k_1/k_0) - 1$ (from eq 5) and $k_i/k_s = k_1/(k_0/K_{\text{app}})$ (from eqs 5 and 6).

still not completely leveled off for all the salts, the consistently greater magnitude of k_{α} is the same as observed with many other substrates examined by Winstein and co-workers.¹ This behavior is compatible with the initial formation of intimate ion pairs which undergo significant return to covalent substrate even at high [salt], while those ion pairs that dissociate to solvent-separated ion pairs are essentially totally scavenged at high [salt].

The effect of added LiClO_4 is to enhance k_{α} by factors of about 1.4 compared to the same concentrations of the trifluoroacetate and triflate salts. The effect of LiClO_4 on k_{UV} is greater, and so the ratio k_{α}/k_{UV} decreases more rapidly for LiClO_4 compared to the other salts, and is only 1.37 at 0.0991 M salt. This effect is consistent with LiClO_4 being more

efficient than the trifluoroacetate and triflate salts in capturing solvent-separated ion pairs. The somewhat greater acceleration of k_{α} by LiClO_4 compared to the other salts is most simply explained as due to a greater effect of this salt on increasing the ionizing power of the medium, but could also result from a specific interaction of the salt with the covalent substrate. This question is under further study.

Common Ion Rate Effects. The effect of 0.0967 and 0.300 M added NaOTs is to decrease the rate constant k_{UV} by factors of 13 and 10%, respectively (Table 1). This behavior is an example of common ion rate depression, combined with a rate-enhancing effect due to "normal" salt effects.^{1d,11c} This result is explained by the formation to a small extent in these reactions of dissociated ions which react with added NaOTs to reform solvent-separated ion pairs which return to starting material. Added 0.260 M NaOTs causes an increase in k_{α} of 17%, as expected for a normal salt effect, although the magnitudes of the rate increases for the trifluoroacetate and triflate salts are larger by factors of 1.4–1.9.

¹⁸O Scrambling. The minimum fractions of ion pair return, $1 - F$, as calculated from the ¹⁸O scrambling by eq 14 (Table 2) in TFA are 0.94 and 0.46 at $[\text{NaO}_2\text{CF}_3] = 0.0$ and 0.201 M, respectively. These are the same or slightly greater than the fractions 0.93 and 0.37, respectively, calculated from k_{α} and indicate that ¹⁸O scrambling is only modestly more effective in the ion pairs than is racemization.

As summarized in Table 2, these ¹⁸O results also show large but somewhat reduced values for the minimum amount of ion pair return, $1 - F$, in other more nucleophilic solvents, namely 0.25, 0.31, 0.66, 0.60, and 0.57 for EtOH, 80% acetone, HOAc, 97% TFE, and 97% HFIP, respectively. We have recently reported^{6c} results for ¹⁸O scrambling in α -(*tert*-butyl)benzyl tosylates and 2-adamantyl tosylate^{7d} in several solvents, and these give comparable values for $1 - F$. However, the value of 0.94 for **3** in TFA without salt is considerably larger than these, and fluorinated benzylic substrates such as **1** and **3** are unique in showing the very large salt effects.^{5a} Thus for 2-adamantyl tosylate the values of $1 - F$ are 0.62 and 0.55 with no salt and 0.1 M NaO_2CCF_3 ,^{6d} respectively, as compared to the values of 0.94 and 0.46 for **3** with no salt and 0.2 M NaO_2CCF_3 . The large salt effects are associated with carbocations that are extensively delocalized and slow to react with nucleophiles^{5a,b,11} and evidently give solvent-separated ion pairs that favor ion pair return as opposed to solvent capture.

Taken together the scrambling and racemization results indicate that the trifluoroacetylolysis of **3** occurs by ionization to an intimate ion pair that undergoes partial racemization and oxygen exchange followed to some extent by internal return. The intimate ion pair subsequently forms solvent-separated ion pairs that undergo further ¹⁸O scrambling and complete racemization. In the absence of added salts the solvent-separated ion pairs undergo extensive return to intimate ion pairs and starting material, which is reformed to the extent of at least 93–94%. The forward and reverse rate constants for formation of the solvent-separated ion pair in the absence of salt both must considerably exceed the rate of capture of the solvent separated ion pair, which is extensively equilibrated with the intimate ion pair in the absence of salt. This is expressed quantitatively in the ratio k_{-1}/k_s (the ratio of return of the ion pair to the covalent substrate compared to capture by solvent), which has values of 35–105 (Table 3). On the addition of salts the capture of the solvent-separated ion pairs is greatly accelerated by k_t (eq 3).

Racemization of ROTs as measured by k_{α}/k_{UV} is reduced to values of 1.07–1.48, but it is still significant, and if all the solvent-separated ion pairs are being trapped at this concentration of salt, this represents the minimum amount of return that occurs from the intimate ion pairs.

In relevant recent work using time-resolved picosecond spectroscopy Yabe and Kochi^{2c} studied the behavior of intimate (contact) ion pairs generated by laser flash photolysis of 9-substituted anthracene complexes with tetranitromethane. Added salts were found to reduce the fraction of the intimate ion pairs that returned to product, and this was proposed to result from ion exchange in the intimate ion pair. It was pointed out^{2c} that such ion pair exchange of the intimate ion pair was not originally included in the Winstein scheme. Our results do not preclude ion pair exchange in the intimate ion pairs, and other solvolytic reactions have been interpreted^{4a} to involve such exchange. However, under our conditions, k_{α} always exceeds k_{UV} , and so even at the highest [salt] studied there is some return from intimate ion pairs.

In conclusion, the agreement between the results of the racemization and scrambling studies, and the consistent behavior of the trifluoroacetate and triflate salts, confirms the high degree of ion pair return of highly delocalized benzylic carbocations in trifluoroacetic acid. Together with the common ion rate effects these are supportive of the operation of the mechanism of eq 1, with the formation of intimate and solvent-separated ion pairs, and the further capture of dissociated ions by the common ion effect. Delocalized benzylic carbocations substituted with destabilizing fluorinated substituents display uniquely large degrees of ion pair return as opposed to solvent capture, particularly in TFA, and this is a further distinctive characteristic of these species.

Experimental Section

Materials. The trifluoroacetate and triflate salts were obtained from Aldrich with the purities listed in parentheses: LiO_2CCF_3 (95%), NaO_2CCF_3 (98%), KO_2CCF_3 (98%), $\text{LiO}_3\text{-SCF}_3$ (96%), and NaO_3SCF_3 (98%). These were dried at 100 °C in an oven and kept in a desiccator under N_2 . For selected runs LiO_2CCF_3 and NaO_2CCF_3 were generated from Li_2CO_3 and Na_2CO_3 , respectively, with $\text{CF}_3\text{CO}_2\text{H}$ and $(\text{CF}_3\text{CO})_2\text{O}$, and these solutions gave the same kinetic behavior.

Solvents. Ethanol, acetone, 2,2,2-trifluoroethanol (TFE), acetic acid, and water were purified as reported before.⁶ 1,1,1,3,3,3-Hexafluoroisopropyl alcohol (HFIP) was directly used as obtained from Central Glass Co. Ltd. Trifluoroacetic acid for ¹⁸O studies was distilled after reflux with trifluoroacetic anhydride for 3 h, and a center boiling fraction was collected. For UV studies trifluoroacetic anhydride was not added because of its UV absorption. The 80% acetone was mixed from the corresponding volume of acetone and water at 25 °C, and 97% TFE and 97% HFIP were mixed from the corresponding weights of alcohol and water.

(+)-1-(4-Tolyl)-2,2,2-trifluoroethanol (5). To a flame-dried 50 mL three-neck flask under Ar, equipped with a condenser and magnetic stirrer, were added (–)-*B*-diisopinocampheylchloroborane [(–)-DIPCl, Aldrich] (3.66 g, 0.0114 mol) and 10 mL of ether. 4-Tolyl trifluoromethyl ketone (**4**, 2.0 g, 0.0106 mol) was added slowly at room temperature, followed by 5 mL of ether, and the solution was stirred for 2.5 days. The solution was then transferred by pressure using a double-tipped needle to a 50 mL round-bottom flask, and the ether and pinene were removed under vacuum. Ether (30 mL) and diethanolamine (2.89 g, 0.027 mol) were added giving an exothermic reaction with gas evolution. After 1.5 h, the mixture was filtered with

(11) (a) Richard, J. P.; Amyes, T. L.; Bei, L.; Stubblefield, V. *J. Am. Chem. Soc.* **1990**, *112*, 9513–9519. (b) McClelland, R. A.; Cozens, F. L.; Steenken, S.; Amyes, T. L.; Richard, J. P. *J. Chem. Soc., Perkin Trans. 2* **1993**, 1717–1722. (c) Richard, J. P. *J. Org. Chem.* **1992**, *57*, 625–629.

suction and washed twice with pentane and the solvent was evaporated, giving 3.74 g of crude product which by ^1H NMR contained **5** and **4**, in a 4/1 ratio, plus pinene signals. The mixture was purified by radial chromatography (1/9 EtOAc/hexanes on silica gel) and the alcohol fraction rechromatographed several times to give (+)-**5**⁹ (0.80 g, 0.0042 mol, 40%); mp 43–43.5 °C; ^1H NMR (CDCl_3) δ 2.38 (s, 3, $\text{CH}_3\text{-Ar}$), 2.43 (d, 1, $J = 4.6$ Hz, CHOH), 4.99 (dq, 1, $J_{\text{HF}} = 6.7$ Hz, $J_{\text{HOH}} = 4.6$ Hz, CHOH), 7.23 and 7.37 (each d, 2, Ar); $[\alpha]_{\text{EtOH}}^{25}$ (average optical rotation from two different concentrations) $36.5 \pm 2.5^\circ$ (589 nm) [lit.⁹ 32.8° , 100% ee], $32.0 \pm 2.4^\circ$ (578 nm), $35.5 \pm 2.2^\circ$ (546 nm), $60.6 \pm 2.6^\circ$ (436 nm).

(+)-**1-(4'-Tolyl)-2,2,2-trifluoroethyl Tosylate (3)**. To a flame-dried three-neck flask under Ar equipped with a condenser and magnetic stirrer was added NaH (50% oil suspension, 0.1 g, 2.1 mmol) which was washed with pentane and with ether, and 10 mL of ether was added. Alcohol (+)-**5** (0.150 g, 0.789 mmol) in 10 mL of ether was added, and the solution was stirred for 1 h at 25 °C and cooled in ice. Then TsCl (0.145 g, 0.761 mmol) in 10 mL of ether was added, and the mixture was stirred overnight. Ice water was added, and the solution was extracted three times with ether. The ether layer was washed with NaHCO_3 and saturated NaCl, dried over CaSO_4 , and then evaporated to give crude **3** (0.225 g, 0.655 mmol, 83%). Recrystallization from pentane/ether gave (+)-**3** (0.151 g, 0.439 mmol, 56%) as white flakes: mp 107–108 °C; ^1H NMR (CDCl_3) δ 2.34 (s, 3, CH_3Ar), 2.40 (s, 3, CH_3Ar), 5.63 (q, 1, $J_{\text{HF}} = 6.3$ Hz, CHO), 7.09–7.68 (m, 8, 2 Ar); $[\alpha]_{\text{CDCl}_3}^{25}$ (average of two concentrations) $63.5 \pm 0.7^\circ$ (589 nm), $67.8 \pm 0.6^\circ$ (578 nm), $78.1 \pm 1.0^\circ$ (546 nm), $137.7 \pm 1.0^\circ$ (436 nm).

(+)-**1-(4'-Tolyl)-2,2,2-trifluoroethyl Trifluoroacetate ((+)-7)**. To a mixture of alcohol (+)-**5** (0.0969, 0.510 mmol) and 50 μL (0.62 mmol) of pyridine in a 5 mL round-bottom flask was added 130 μL (0.920 mmol) of trifluoroacetic anhydride, with immediate formation of a precipitate. Ice water was added, and the aqueous layer was extracted three times with ether. The combined ether extracts were washed with cold NaHCO_3 solution and saturated NaCl, dried over CaSO_4 , and evaporated to give 0.0986 g of crude product which by ^1H NMR contained 9% residual (+)-**5** along with the product. This was purified by VPC (OV-17 column, 90 °C, retention time 8 min) to give (+)-**7**: ^1H NMR (CDCl_3) δ 2.39 (s, 3, CH_3Ar), 6.18 (q, 1, $^2J_{\text{HF}} = 6.4$ Hz, CHCF_3), 7.23 and 7.37 (each d, 2, $J = 8.1$ Hz, ArH); $[\alpha]_{\text{CDCl}_3}^{25}$ (average of two concentrations) $112.3 \pm 0.1^\circ$ (578 nm), $130.1 \pm 0.3^\circ$ (546 nm), $236.6 \pm 1.0^\circ$ (436 nm); $[\alpha]_{\text{CF}_3\text{CO}_2\text{H}}^{25}$ 105.4° (546 nm), 195.0° (436 nm). The rotations in $\text{CF}_3\text{CO}_2\text{H}$ did not change over 18 h.

Recovery of (+)-3 from trifluoroacetylolysis. The rotation of a solution of (+)-**3** (0.0449 g, 0.130 mmol) in 10 mL of TFA was observed for 1.5 h, and α_{obsd} decreased from 0.66 to 0.0. The reaction mixture was poured into ice water and pentane, and the pentane layer was extracted with cold NaHCO_3 and with cold NaCl solution. The solvent was evaporated, giving 0.0382 g of product which by ^1H NMR analysis showed the presence of the tosylate **3** and the trifluoroacetate **7** in a 0.917 to 0.083 ratio. The observed rotation of the product at four wavelengths corresponded to $1.4 \pm 0.1\%$ residual optical activity for (+)-**3**, assuming zero rotation for the trifluoroacetate **7** formed. From the measured k_{UV} and k_{α} values 74% of **3** should remain after this time, with 1.3% residual optical activity.

Kinetics. The salt solutions were made up by dilution of 0.6 M solutions to various concentrations. Rates of solvolysis were measured by injecting 5 μL samples of 0.3 M solutions of **3** in CH_3CN into 1.2 mL of solvent in a thermostated UV

cell and observing the decrease in the absorbance at 262 nm ($\Delta A = 0.4$) using a Varian 210 spectrophotometer.

Polarimetric rate constants were measured at 436 nm using a Perkin-Elmer 141 polarimeter. The rates were typically obtained by injecting 20 μL of a 0.434 M (+)-**3** in CH_3CN into 1 mL of temperature-equilibrated solution in a 1 dm polarimeter cell and mixing. Starting rotations were 0.390, and these decreased to 0.000 ± 0.07 during measurement.

4-Toluenesulfonyl-sulfonyl- $^{18}\text{O}_2$ chloride. The sulfonyl- $^{18}\text{O}_2$ -labeled 4-tosyl chloride was prepared according to the procedure of Oae *et al.*¹⁰ Dry chlorine gas was bubbled into the mixture of 4-toluenethiol (10.0 g, 0.081 mol) and H_2^{18}O (5.0 g, 0.250 mol, Isotec Inc., 98.8 atom % ^{18}O) for 4.5 h. Then the reaction mixture was dissolved in ether and the aqueous layer was extracted twice with ether. The combined ether extracts were washed with aqueous sodium chloride and dried over anhydrous magnesium sulfate. The crude product was purified by the combination of column chromatography on silica gel and recrystallization to give 6.42 g (41%) of labeled *p*-tosyl chloride.

1-(4'-Tolyl)-2,2,2-trifluoroethyl Tosylate-sulfonyl- $^{18}\text{O}_2$. The sulfonyl- $^{18}\text{O}_2$ labeled tosylate was obtained by the coupling of (\pm)-**5** and 4-tosyl-sulfonyl- $^{18}\text{O}_2$ chloride as previously reported.^{5b} To a suspension of sodium hydride (0.014 mol) in 10 mL of ether, (\pm)-**5** (0.894 g, 0.0047 mol) in 15 mL of ether was added dropwise at 0 °C under a nitrogen atmosphere. After the mixture was stirred, for 80 min 4-tosyl-sulfonyl- $^{18}\text{O}_2$ chloride (0.913 g, 0.0047 mol) in 15 mL of ether was added dropwise at 0 °C. The mixture was stirred overnight, then was filtered and concentrated followed by recrystallization from ether/hexane to give 0.979 g (61%) of the tosylate: mp 85.6–86.4 °C; ^1H NMR (CDCl_3) δ 2.31, 2.38 (each s, 3H, CH_3), 5.63 (q, 1, $^2J_{\text{HF}} = 6.3$ Hz, CHCF_3), 7.09, 7.19, 7.20, 7.64 (each d, 2, $J = 8.2$ Hz, ArH); ^{13}C NMR (CDCl_3) δ 21.24, 21.60 (CH_3), 78.13 (q, $^2J_{\text{CF}} = 34$ Hz, CHCF_3), 122.35 (q, $^1J_{\text{CF}} = 281$ Hz, CF_3), 126.81, 133.24, 140.47, 145.30 (2C, tertiary), 127.96, 128.07, 129.34, 129.70 (1C, quaternary).

^{18}O Exchange. Reactions were carried out by procedure A for the slower reactions above room temperature, except for those in trifluoroacetic acid and 97% HFIP, which utilized procedure B. In the case of acetic acid and trifluoroacetic acid, the ether extract was washed with water and aqueous sodium bicarbonate before washing with aqueous sodium chloride. Two independent runs were carried out in the respective solvents except for 100% EtOH.

Procedure A. Starting tosylate (70 mg, 2.0×10^{-4} mol) was sealed in an ampoule with 10 mL of solvent (0.02 M initial ester concentration). The solution was reacted for an elapsed time in a thermostated bath controlled within ± 0.02 °C. The reaction was stopped by rapid cooling with ice water and the contents of the ampule were poured into 150 mL of ice water. The reaction mixture was extracted with ether four times, then the combined ethereal solution was washed with saturated aqueous sodium chloride, dried over anhydrous magnesium sulfate, and concentrated under reduced pressure. The resulting residue was dissolved in benzene- d_6 and was transferred to an NMR tube (5 mm).

Procedure B. Ten mL of solvent equilibrated at 25 °C was added to the starting tosylate (70 mg, 2.0×10^{-4} mol) to make the reaction solution. At an elapsed time, the reaction solution was quenched by pouring into ice water, followed by extraction with ether and treatment as in procedure A.

NMR Measurement. The ^1H -decoupled ^{13}C NMR spectra were recorded on a JEOL JNM-EX270 FT-NMR spectrometer at 67.8 MHz. The conditions employed for the measurement

of ^{18}O scrambling were as follows: data points 8k or 32k, sweep width 250 Hz or 1 kHz (0.061 Hz/pt), and repetition time 29.4 s. At least 20 000 scans were taken for accumulation. The signal for the alkoxy carbon of starting tosylate appeared at 78.28 ppm from TMS based on C_6D_6 at 128.0 ppm as a quartet due to C–C–F coupling ($^2J_{\text{CF}} = 33.9$ Hz). The ^{18}O -induced isotopic shift of each peak was observed at 0.029 ppm (2.0 Hz) higher field. The ratio of ^{16}O -bonded (^{16}OTs) and ^{18}O -bonded (^{18}OTs) carbons was determined from the ratio of integral area for each peak. The center two pairs of all the four pairs of alkoxy carbons were employed for the calculation of the ratio. The smaller outer two pairs were not included in the calculation because of presumed greater uncertainties. The observed ratios of ^{16}O and ^{18}O are listed in Table 2.

Treatment of ^{13}C NMR Data. As collected in Table 2 the concentration of total tosylate was calculated from corresponding solvolysis rate constants, k_{UV} , using eq 10. Calculated ratios

of [product], [^{16}OTs], and [^{18}OTs] were obtained using k_{UV} and [^{16}OTs]/[^{18}OTs]. Assuming that oxygen scrambling is accompanied with complete exchange of three oxygen atoms, the concentration of unscrambled tosylate (ROT_s) was calculated by eq 12 (Table 2).

The minimum rate of ionization, k_i , is obtained from decrease of [unscrambled OT_s] by eq 13. Obtained rate constants k_{UV} and k_i are listed in Table 2 together with the minimum fraction of internal return, $1 - F$, in eq 14.

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